

Generation of cylindrical vector vortex beams by two cascaded metasurfaces

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Abstract: We present a simple and efficient method to generate any cylindrical vector vortex (CVV) beams based on two cascaded metasurfaces. The metasurface works as a space-variant Pancharatnam-Berry phase element and can produce any desirable vortex phase and vector polarization. The first metasurface is used to switch the sign of topological charges associated with vortex, and the second metasurface is applied to manipulate the local polarization. This method allows us to simultaneously manipulate polarization and phase of the CVV beams.

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1. Introduction

Polarization and phase are two fundamental features of electromagnetic waves. Conventional polarization states, such as linear, circular, and elliptical polarizations, are spatially homogeneous. Recently, light beams with a spatial inhomogeneous polarization distribution (vector beams) have drawn much attention [1]. Most existing researches were devoted to the case of polarization state with cylindrical symmetry distribution (cylindrical vector beam) because of their distinctive properties and potential applications [2–9]. Comparing with the conventional homogeneous polarization represented by the fundamental Poincaré sphere and orbital Poincaré sphere [10–12], the cylindrical vector beams can be represented by a higher order Poincaré sphere [13–15]. On the other hand, optical vortices are intriguing optical structures with spiral wavefronts. The phase around the vortex is characterized by $\exp(im\varphi)$, where m is the topological charge and φ the azimuthal angle. Such beams with optical vortex phase carry orbital angular momentum (OAM) of $m\hbar$ per photon [16]. Vortex beams have found wide applications in optical manipulation, imaging, and optical communication [17]. If an optical beam possesses both vector polarization and helical phase, referred to as cylindrical vector vortex (CVV) beams,

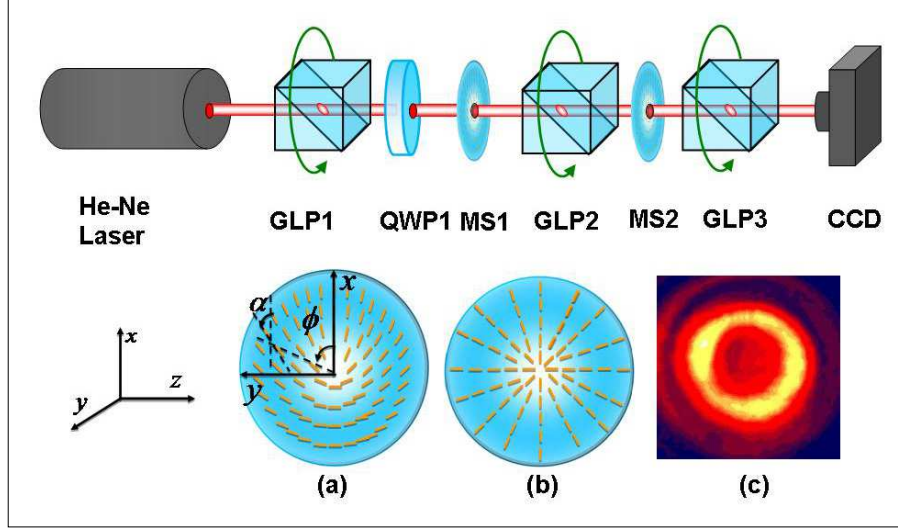


Fig. 1. Experimental setup for generating arbitrary CVV beams. Inset (a) and (b): Schematic pictures of metasurfaces with $q = 0.5$ and $q = 1$, respectively. Space-varying nanograting consisting of nanoscale waveplate with a spatially varying fast axis directions. Inset (c): Intensity distribution of the CVV beams presents doughnut profiles.

it can provide more degrees of freedom for beam manipulation [18].

Driven by their fantastic features and various applications, several methods have been proposed to produce CVV beams, such as a liquid-crystal polarization converter [19], interference of different vector modes [20], spatial light modulator [21], spiral phase plates [22], and forked grating [23]. Recently, metasurface, a two-dimensional electromagnetic nanostructure, is expected to expand the capabilities of existing vortex optics for simultaneous control of intensity, polarization, and phase [24, 25]. A compact metasurface which consists of two concentric rings in a gold film has been proposed to generate the OAM-carrying vector beams [18]. In addition, it has been demonstrated that the polarization states can be controlled by a metasurface fabricated by femtosecond laser writing of self-assembled nanostructures in silica glass [26]. However, the vortex beam in this situation is confined to the two special cases: the radial and the azimuthal polarizations.

In this work, we present a technique to generate CVV beams with a simple optical device based on two cascading metasurfaces. The metasurface is structured by writing a space-variant nanograting in a silica glass. The nanograting structure results in a space-variant effective birefringence. By tunably controlling the local orientation and geometrical parameter of the nanograting, one can achieve any desired polarization manipulation [27–29]. The two dimensional nanostructures have a high transmissivity that allows us to cascade the metasurfaces. The experimental equipment consisted of two metasurfaces can generate CVV beams with arbitrary polarization orientation and allows us to switch the signs of topological charges of vortex by controlling the handedness of incident circular polarization.

2. Metasurface and Pancharatnam-Berry phase

A metasurface is fabricated by femtosecond laser writing of self-assembled nanostructures in silica glass [26]. The writing pattern is locally varying and of the order less than a wavelength. This leads to build an artificial uniaxial crystal with homogeneous phase retardation δ at the

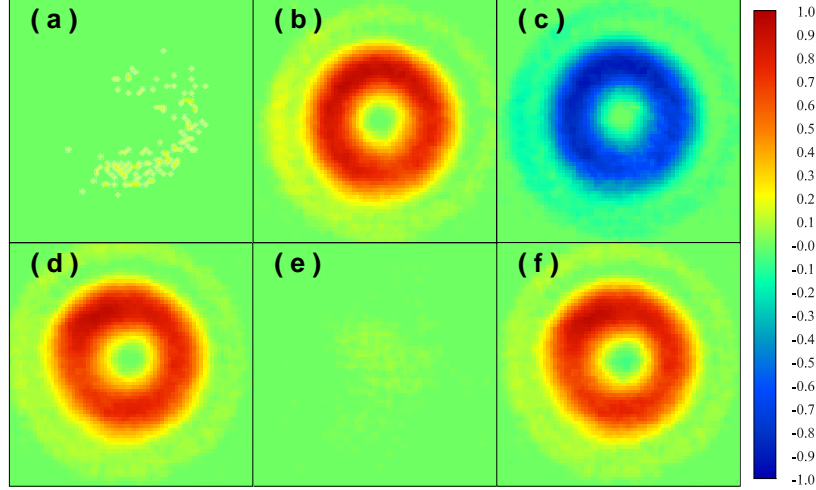


Fig. 2. Stokes parameter S_3 of the beams emerging from MS1. Row 1: the experimental results when QWP1 is placed at 45° . (a) and (b) are the intensity distributions when GLP4 is placed at $\pm 45^\circ$, respectively. (c) the corresponding Stokes parameter S_3 . Row 2: the experimental results when QWP1 is placed at -45° . (d) and (e) are the intensity distributions when GLP4 is placed at $\pm 45^\circ$, respectively. (f) the corresponding Stokes parameter S_3 .

working wavelength λ and locally varying optical axes direction parallel and perpendicular to the writing direction of the nanostructure in the transverse plane (xy). As the dimension of the nanograting structure is smaller than the incident wavelength, only the zero order is a propagating order, and all other orders are evanescent [30].

In particular, the optical axis direction can be specified by the following expression:

$$\alpha(r, \varphi) = q\varphi + \alpha_0, \quad (1)$$

where (r, φ) is the polar coordinate representation, α_0 is a constant angle specifying the initial orientation for $\varphi = 0$, and q is a constant specifying the topological charge of the metasurface. The manipulation of polarization state and wavefront is obtained by using the effective birefringence of the nanostructure.

If the orientation of the nanostructure is space-variant at each location, the grating can be described by the coordinate-dependent matrix [31–33]:

$$\mathbf{T}(r, \varphi) = \mathbf{M}(r, \varphi) \mathbf{J} \mathbf{M}^{-1}(r, \varphi). \quad (2)$$

Here, \mathbf{J} is the Jones matrix of a uniaxial crystal, and

$$\mathbf{M}(r, \varphi) = \begin{pmatrix} \cos \alpha & \sin \alpha \\ \sin \alpha & -\cos \alpha \end{pmatrix}, \quad (3)$$

where $\alpha(r, \varphi)$ is the local optical axis orientation of the metasurface. It is easily derived that the Jones matrix $\mathbf{T}(r, \varphi)$ can be written as

$$\mathbf{T}(r, \varphi) = \cos \frac{\delta}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + i \sin \frac{\delta}{2} \begin{pmatrix} \cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha \end{pmatrix}. \quad (4)$$

Let us now consider that the metasurface is normally illuminated by a circularly polarized vortex wave with spin angular momentum (SAM) $\sigma\hbar$ and OAM $m\hbar$, where $\sigma = +1$ for the

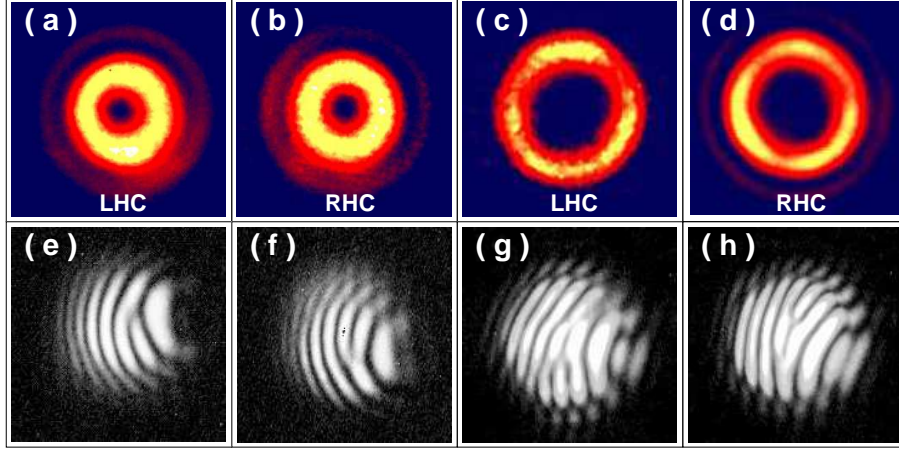


Fig. 3. The intensity distribution (upper panels) of the beam emerging from the first metasurface and the interference patterns (lower panels) after their superposition with the reference beam. (a) and (b) are intensities for the LHC and RHC polarization incidence, and (e) and (f) are interference patterns with the reference beam, respectively, for $m = 1$. (c) and (d) as well as (g) and (h) are the corresponding results for $m = 2$.

left-handed circular (LHC) case and $\sigma = -1$ for the right-handed circular (RHC) one. Its Jones vector is then given by $\mathbf{E}_{in}(r, \varphi) = E_0(r, \varphi) \times [1, \sigma i] \exp(im\varphi)$. The output beam $\mathbf{E}_{out}(r, \varphi) = \mathbf{T}(r, \varphi) \mathbf{E}_{in}(r, \varphi)$ can be written as

$$\mathbf{E}_{out}(r, \varphi) = E_0 \cos \frac{\delta}{2} \exp(im\varphi) \begin{pmatrix} 1 \\ \sigma i \end{pmatrix} + iE_0 \sin \frac{\delta}{2} \exp[i(m\varphi + 2\sigma\alpha)] \begin{pmatrix} 1 \\ -\sigma i \end{pmatrix}. \quad (5)$$

We find that the output field can be regarded as a superposition of a part that has the same SAM and OAM as the input one, and another part having a reversed SAM and a modified OAM given by $(m + 2\sigma\alpha)\hbar$. It means that the input light beam only partially converts its spin angular momentum to its orbital part [33]. When $m = 0$, Eq. (5) represents the case of that the metasurface is illuminated by a circularly polarized light. The amplitudes of these two components of the output field depend on the birefringent retardation δ , i.e., $\cos \delta/2$ and $\sin \delta/2$, respectively.

More interestingly, the output field acquires a nonuniform phase retardation. In general, any desirable wavefront can be generated by designing the metasurface geometry. The second term of Eq. (5) indicates a polarization orthogonal to that of the input wave, and its phase is twice of the local optical axis orientation $2\sigma\alpha$. Similarly, the wavefront with an opposite topological charge should be generated if the input polarization handedness is inverted. This particular approach for optical wavefront shaping is purely geometric in nature, and the additional phase factor is the so-called Pancharatnam-Berry geometric phase [31]. The wavefront-shaping device based on this principle have been realized and can be referred to as Pancharatnam-Berry phase optical element [27].

As a special case, a homogeneous half waveplate can completely convert a LHC (RHC) polarization into a RHC (LHC) polarization. The circular polarized input light reverses its handedness and acquires a constant phase factor when passing through the half-wave plate. But the inhomogeneous anisotropic metasurface can result in the occurrence of the spin-orbit interaction [30]. As expected, a half-wave metasurface ($\delta = \pi$) not only can invert the handedness of circular polarization, but also applies the output wave an azimuthal phase, i.e., OAM. It is well known that LHC and RHC polarized light possess angular momentum of $\pm\hbar$ per photon. From

Eq. (5), a LHC polarized incident light can be transformed into a RHC polarized vortex light. Thus the spin-orbit interaction in the metasurface leads to the appearance of the helical phase with topological charge $2q$. Similarly, for the right-handed circular polarization incidence, a left handed circular polarization vortex light with topological charge $-2q$ will be gotten.

Let us now consider that the metasurface is illuminated by a linear polarized vortex wave whose Jones vector is then given by $\mathbf{E}_{in}(r, \varphi) = E_0(r, \varphi) \times [\cos \theta, \sin \theta] \exp(im\varphi)$. The output beam $\mathbf{E}_{out}(r, \varphi) = \mathbf{T}(r, \varphi)\mathbf{E}_{in}(r, \varphi)$ can be obtained as

$$\mathbf{E}_{out}(r, \varphi) = E_0(r, \varphi) e^{im\varphi} \begin{pmatrix} \cos(2\alpha - \theta) \\ \sin(2\alpha - \theta) \end{pmatrix}. \quad (6)$$

Here, we have assumed $\delta = \pi$. From Eq. (6) we can see that the output beam is a CVV beam. It means that the metasurface can apply to change the spatial distribution of polarization. This interesting phenomenon can be explained as the appearance of the Pancharatnam-Berry phase when the beam passes through the metasurface [31, 33]. By rotating the incident polarization, the polarization direction of the CVV beam can be tunable effectively.

3. Experimental results and discussions

Figure 1 shows the schematic illustration of the experimental setup for generating arbitrary CVV beams. In the experiment, we use a paraxial Gaussian beam as the light source, which is produced by a He-Ne laser working at the wavelength $\lambda = 632.8 \text{ nm}$. The laser beam is converted to linear polarization state by a Glan laser polarizer (GLP1). The angle between the fast axis of the quarter-wave plate (QWP1) and the transmission axis of the GLP1 is arranged at 45° . The linear polarized beam is converted into a left-handed circular polarization by QWP1. The first metasurface (MS1) is used to transform the LHC (RHC) polarization beam into RHC (LHC) polarization with a helical phase. Figure 1(a) and 1(b) present two schematic pictures of the metasurface. In our scheme, the metasurface is fabricated by femtosecond laser writing of self-assembled nanostructures in a silica glass (Altechna). In principle, the metasurface can be regarded as a two dimensional aperiodic nanograting, which can produce space-variant phase and polarization.

As mentioned above, the QWP1 in our experimental setup is placed at $\pm 45^\circ$ in order to generate a left- or right-handed circularly polarized beam. And then, the first metasurface will convert the LHC (RHC) beam into a RHC (LHC) polarized vortex beam. To obtain the polarization distribution, the Stokes parameter are measured [34]. As shown in Fig. 1, we can add another Glan laser polarizer (GLP4) and another quarter waveplate (QWP2) behind the MS1. By rotating the GLP4 to two angles ($\pm 45^\circ$) and holding QWP2 in the x direction, we can obtain the intensity distributions on the CCD. As the Stokes parameter S_3 is defined as $S_3 = (I_{+45^\circ} - I_{-45^\circ}) / (I_{+45^\circ} + I_{-45^\circ})$, where $I_{\pm 45^\circ}$ represents the recorded intensity when the transmission axis of the GLP4 is set as $\pm 45^\circ$. After a series of data process, we can obtain the S_3 pixel by pixel. The experimental results indicate that the MS1 transforms the LHC polarization beam into the RHC polarization one and vice versa, as shown in Fig. 2.

To observe the phase structure of the generated vortex beams, we measure the interference pattern between the vortex beam and the reference beam which is split from the input Gaussian beam. The second metasurface is applied to change the spatial distribution of polarization. By rotating GLP2, the polarization direction of the CVV beam can be easily modulated. The polarizer (GLP3) acts as a polarization analyzer, and the CCD camera is used to record the transmitted intensity distribution. The experimental results are plotted in Fig. 3. Figure 3(a) and 3(b) show the intensity distribution of the RHC and the LHC polarized vortex beam with topological charge $m = 1$, respectively. The interference patterns of the LHC (RHC) polarized incident case with the reference beams are shown in Fig. 3(e) and 3(f). This fork-like patterns

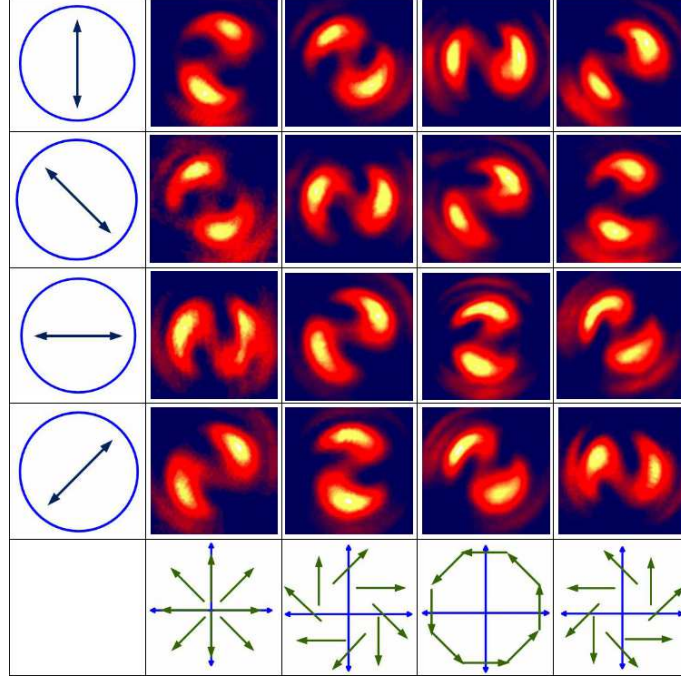


Fig. 4. A set of experimentally generated CVV beams when GLP1 is placed at $+45^\circ$. The first column shows the direction of the linear polarizer (GLP3). The next four columns show the intensity distributions behind the polarization analyzer at different polarization angles. The lowest row sketches the reconstructed vector fields of the output beams

indicate the phase vortices in the LHC (RHC) polarized beams. Additionally, we also implement a group of experiments for $m = 2$.

The second metasurface (MS2) is applied to change the spatial distribution of polarization. We set the transmission axis of the GLP2 inclined an angle of θ respect to the x direction. The emerging beam from the GLP2 can be written as $E_0(r, \varphi)e^{i\varphi}[\cos \theta, \sin \theta]$. This is a linear polarization vortex beam. From Eq. (6), the expression of the output beam after the MS2 can be written as

$$\mathbf{E}_{out}^{II}(r, \varphi) = E_0(r, \varphi)e^{i\varphi} \begin{pmatrix} \cos(2\varphi - \theta) \\ \sin(2\varphi - \theta) \end{pmatrix}. \quad (7)$$

From Eq. (7), we can see that the output field is a CVV beam with topological charge $+1$. One can obtain a vortex beam with arbitrary polarization direction by rotating the GLP2. In principle, the incident linear polarized beam can be regarded as a superposition of LHC polarized and RHC polarized waves. Therefore, the output CVV beam is the coherent superposition of a LHC polarized vortex and a RHC polarized vortex beam [Eq. (5)]. That is to say, there appears a spin-dependent phase, the so-called Pancharatnam-Berry phase, when the beam passes through the MS2.

We now consider that a RHC polarized beam illuminates the MS1 by setting the transmission axis of the GLP1 at $+45^\circ$. Figure 4 shows the measured intensity distributions when the GLP2 is rotated at different angles. According to the measured intensity distributions by rotating the polarization analyzer GLP3, the polarization states of the output beams are sketched in the lowest row. In Fig. 4, we can clearly observe a typical anti-“s”-shape pattern which is led by the helical phase with topological charge -1 . The mode in the second column corresponds to

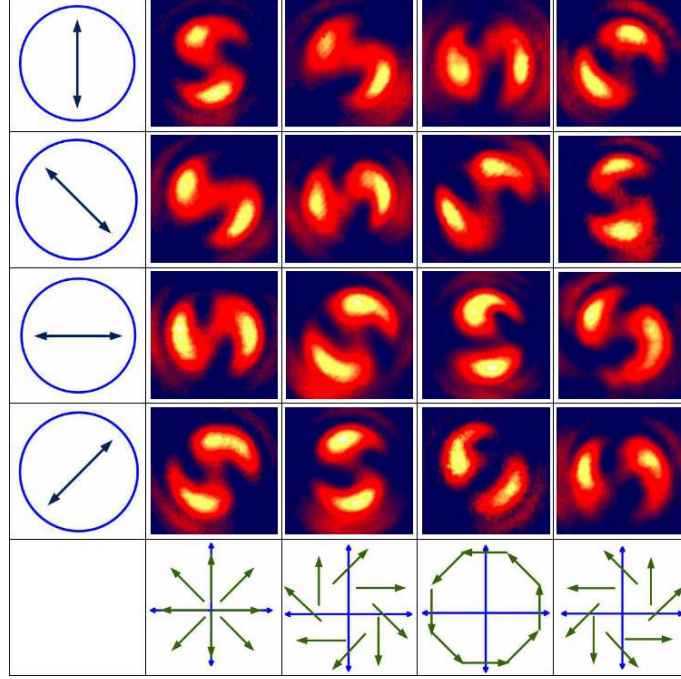


Fig. 5. A set of experimentally generated CVV beams when GLP1 is placed at -45° . The first column shows the direction of the linear polarizer (GLP3). The next four columns show the intensity distributions behind the polarization analyzer GLP3 at different polarization angles.

a radially polarized vortex beam with GLP2 placed at 0° angle. Rotating the GLP2 at 45° , we can obtain a polarized vortex beam with local polarization direction rotated 45° as shown in the third column. When GLP2 is placed at 90° , a vortex beam with azimuthal polarization can be obtained as displayed in the fourth column. And the fifth column corresponds to a polarized vortex beam with GLP2 placed at -45° .

We also carry out another group of experiment when GLP1 is placed at -45° . This means that a LHC polarized beam illuminates on the MS1. The experimental results are shown in Fig. 5. We find that the intensity pattern is changed into “s” shape. It suggests that the topological charge of the helical phase is $+1$, which is opposite to the case shown in Fig. 4. The experimental results agree well with the theoretical predictions. From the above experimental results, we can see that our CVV beam converter can generate any desired CVV beams which is not confined to the radial and azimuthal cases [26], and also not restricted to the topological charge $m = 1$. Such a CVV beam converter enables us to simultaneously manipulate the wavefront and the polarization state of light.

4. Conclusions

In conclusion, we have proposed and realized a simple cylindrical vector vortex (CVV) beam converter with two cascaded metasurfaces. Based on spin-orbit interaction, the first metasurface can switch the topological charges between positive and negative vortices by controlling the handedness of incident polarization. The second metasurface can manipulate the local polarization orientation of vector beam. The whole system forms a compact optical system that provides a simple method to produce CVV beams with any desirable polarization and vortex phase. The

ability to simultaneously tailor the wavefront and the polarization state of light is expected to hold potential applications in the fields of optical communication and mode switching.

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